Appendix B

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Leakage through Liners Constructed with Geomembranes—Part I. Geomembrane Liners*

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ABSTRACT

How impermeable are 'impermeable liners'? All liners leak, including geomembranes, but how much? What are the mechanisms of leakage through liners constructed with geomembranes? To answer these questions, a detailed review of leakage mechanisms, published and unpublished test data, and analytical studies has been carried out with the goal of providing practical design recommendations. In particular, it appears that a composite liner (i.e. geomembrane on low-permeability soil) is more effective in reducing the rate of leakage through the liner than either a geomembrane alone or a soil liner (low-permeability soil layer) alone. However, the paper shows that the effectiveness of composite liners depends on the quality of the contact between the geomembrane and the underlying low-permeability soil layer.

NOTATION

A	Area (m^2)
A_s	Cross-sectional area of flow in soil (m^2)
a	Hole area (m^2)
B	Width (m)
b	Width of a two-dimensional hole (slot) in the geomembrane (m)
C_B	Dimensionless coefficient
C_F	Dimensionless coefficient

*Part II of this paper will follow in *Geotextiles and Geomembranes* 8(2).

C_1	Coefficient in the relationship between coefficient of migration and pressure difference (dimension depends on relationship)
d	Hole diameter (m)
D_g	Water vapor diffusion coefficient of geomembrane (s)
g	Acceleration due to gravity (m/s^2) (note: $g = 9{\cdot}81$ m/s^2)
H	Relative humidity of water vapor (dimensionless)
ΔH	Relative humidity difference (dimensionless)
H_L	Liner thickness (m)
H_s	Soil layer thickness (m)
h	Hydraulic head (m)
Δh	Hydraulic head difference (m)
h_w	Depth of liquid on top of the geomembrane (m)
i	Hydraulic gradient (dimensionless)
i_s	Vertical hydraulic gradient in soil (dimensionless)
k	Hydraulic conductivity (m/s)
k_g	Equivalent hydraulic conductivity of geomembrane (m/s)
k_p	Hydraulic conductivity of geotextile within its plane (m/s)
k_s	Hydraulic conductivity of soil layer (m/s)
M	Mass (kg)
m	Coefficient of migration (m^2/s)
m_g	Geomembrane coefficient of migration (m^2/s)
m_{gmax}	Maximum value of geomembrane coefficient of migration (m^2/s)
n	Exponent in eqn (19) (dimensionless)
p	Pressure (Pa)
Δp	Pressure difference (Pa)
$\Delta p_{plateau}$	Value of pressure difference where m_g reaches its plateau (Pa)
p_s	Pressure of saturated water vapor (Pa)
Q	Flow rate, leakage rate (m^3/s)
Q_g	Leakage rate due to geomembrane permeation (m^3/s)
Q_i	Interface flow rate (i.e. flow rate in the space between geomembrane and underlying soil) (m^3/s)
Q_r	Radial interface flow rate (m^3/s)
Q_s	Flow rate into the soil (m^3/s)
Q^*	Leakage rate per unit length in the direction perpendicular to the figure (m^2/s)
q	Unitized leakage rate (i.e. leakage rate per unit area of liner) (m/s)
q_g	Unitized leakage rate due to geomembrane permeation (m/s)
R	Radius of wetted area (m)
r	Radius (m)

s Spacing between geomembrane and underlying soil (m)
T Thickness (m)
T_g Geomembrane thickness (m)
t Time (s)
WVT Water vapor transmission rate (kg/(m^2 s))

η Viscosity of liquid (kg/(m s))
θ Hydraulic transmissivity of the medium between the geomembrane and the underlying soil (m^2/s)
ρ Density (kg/m^3)

1 INTRODUCTION

1.1 Scope

1.1.1 Some essential questions

Geomembranes are becoming the most commonly used material for the lining of containment facilities used to store water, chemicals, ore and waste. The use of geomembranes is mandatory in some countries for the lining of certain types of waste containment facilities, e.g. hazardous waste landfills and liquid impoundments. Even when municipal solid waste reduction processes are used (e.g. composting, recycling, incineration) there is still a substantial fraction of the waste (sometimes more than 50%) which must be landfilled and, when landfills are located over an aquifer, they should be lined.

Geomembranes are relatively new as compared to other lining materials, such as clay, concrete and asphaltic concrete. As a consequence, many questions arise when their use is considered. These include:

- *Engineer's questions at the conceptual design stage.* Should a geomembrane be placed on a low-permeability soil layer (thereby forming a geomembrane–soil composite liner), or should the geomembrane be placed directly on a drainage layer to collect leakage?
- *Engineer's questions at the detailed design stage.* How can leakage through a geomembrane be evaluated, and what is the influence of the permeability of the underlying soil? What size and number of geomembrane defects should be considered in leakage rate calculations? If a layer of low-permeability soil is placed under a geomembrane (to form a composite liner) what are the required properties of this soil layer? What is the influence of hydraulic head on the leakage rate through the liner? For composite liners, does a geotextile placed

between the geomembrane and the low-permeability soil layer significantly affect the leakage rate if there is a defect in the geomembrane?

- *Installer's and quality assurance monitor's question.* How critical are defects in a geomembrane due to puncture, inadequate seams, etc.?
- *Regulator's and specifier's question.* What 'reasonable' leakage rates should be considered in regulations and specifications?
- *Owner's question.* Should geomembranes be used alone or in association with low-permeability soils to meet performance criteria imposed in regulations and specifications?
- *Responsible citizen's question.* To what degree do geomembranes help protect human health and the environment when they are used for the lining of facilities containing waste or other potentially dangerous materials?
- *Researcher's question.* In which area of leakage evaluation do we need additional research?

All these questions are essential, considering that, for many years to come, storage and disposal in containment facilities will probably be the most practical way for handling waste, and water conservation will be a challenge that many societies will have to face.

1.1.2 Purpose and organization of this paper

The purpose of this paper is to present the state of the art regarding the above questions. A detailed review of leakage mechanisms, published and unpublished test data, and analytical studies are presented in two main sections:

- a section devoted to geomembrane liners placed directly on a pervious soil; and
- a section devoted to composite liners comprised of a geomembrane placed on a low-permeability soil layer.

The last section of the paper presents practical conclusions.

The remainder of this introduction presents general information on liners and lining systems and gives basic definitions regarding leakage.

1.2 Liners

1.2.1 Definition of liner

A liner is a low-permeability barrier used to impede liquid or gas flow. Note that 'low-permeability' is used, and not 'impermeable'. If there was such a thing as an impermeable barrier, it would be possible to prevent leakage, and many of the discussions and considerations presented in this paper would be pointless. Although a glass may appear to be impermeable to water, none of the materials presently used in civil engineering to line large areas is impermeable.

1.2.2 Liner materials

Low-permeability materials used in civil engineering to construct liners include: low-permeability soils, geomembranes, concrete and asphaltic concrete. Only low-permeability soils and geomembranes are discussed in this paper:

- Low-permeability soils used to construct liners include clays, silty clays, clayey sands and silty sands. If such soils are not available at the site, it is possible to make a low-permeability soil by mixing bentonite with a more permeable soil such as sand.
- Geomembranes are low-permeability membranes used in civil engineering as fluid barriers. By definition, a membrane is a material that is thin and flexible. Geomembranes include asphaltic geomembranes and polymeric geomembranes. Examples of materials used to manufacture polymeric geomembranes are: high density polyethylene (HDPE); linear medium density polyethylene (LMDPE); polyvinyl chloride (PVC); and chlorosulfonated polyethylene (CSPE). Basic definitions regarding geomembranes are given by Giroud and Frobel[1] and Giroud.[2]

1.2.3 Composite liner

A composite liner is a liner comprised of two or more low-permeability components made of different materials in contact with each other. For example, a geomembrane and a low-permeability soil layer placed in contact with each other constitute a composite liner (Fig. 1(b)) (p. 34). Composite liners are not double liners, as discussed in Section 1.3.2.

The purpose of a composite liner is to combine the advantages of two materials, such as geomembranes and soils, which have different hydraulic, physical, and endurance properties.

Hydraulic properties. On one hand, the presence of the low-permeability soil component is beneficial:

- Geomembranes may have holes through which large amounts of leakage can occur if the geomembrane is placed on a pervious medium and subjected to a hydraulic head. The leakage rate through a geomembrane hole is reduced by several orders of magnitude, as discussed in this paper, if there is a low-permeability soil under the geomembrane.
- The amount of time (called 'breakthrough time') required for liquid

to flow through a geomembrane can be small. Even if the geomembrane has no hole and flow is only due to permeation, the breakthrough time through a geomembrane can be of the order of a few weeks or less. This is essentially due to the thinness of geomembranes. In contrast, soil layers are thick and the breakthrough time for a 1 m (3 ft) thick low-permeability clay with no cracks can be of the order of 10 years or more.

On the other hand, the presence of the geomembrane component is beneficial because its very low permeability decreases the leakage rate by several orders of magnitude, compared to the leakage rate through a soil liner alone.

The complementarity of the two components of a composite liner from a hydraulic standpoint can be summarized as follows: (i) the geomembrane component decreases the leakage rate, while the low-permeability soil component increases the breakthrough time; and (ii) the presence of the low-permeability soil in contact with the geomembrane decreases the rate of leakage due to a hole in the geomembrane.

Physical properties. The complementarity of the geomembrane and low-permeability soil components of a composite liner is also clear in the area of physical properties. One of the components of a composite liner may retain its integrity while the other is breached, and, in some cases, one of the components protects the integrity of the other:

- On one hand, geomembranes are thin and can be punctured and torn by shocks or concentrated stresses, whereas soil layers are thick and are rarely completely breached by shocks or concentrated stresses. Also, the low-permeability soil, which is smooth and relatively thick, protects the geomembrane from the concentrated stresses which might otherwise be exerted by underlying angular materials.
- On the other hand, clay liners may exhibit cracks, due to small strains or changes in moisture content, while geomembranes retain their continuity under these conditions. In addition, due to their extremely low permeability, geomembranes can prevent desiccation of the low-permeability soil.

Endurance properties. Chemical resistance and aging characteristics of geomembranes and soils are different. Therefore, it is conservative to use two different materials: if one of them does not last as long as predicted, the other may continue to perform. In many cases, this would not be acceptable since all components of a design are normally required to perform. However, this may be sufficient in some cases such as landfills where performance requirements decrease after a certain period of time since leachate generation dramatically decreases after landfill closure.

1.2.4 Terminology related to liners

A geomembrane used alone (i.e. not associated with a low-permeability soil layer) is called a 'geomembrane liner' (Fig. 1(a)). A low-permeability soil layer used alone (i.e., not associated with a geomembrane) is called a 'soil liner' (e.g. a 'clay liner', if the soil is a clay).

The geomembrane and the low-permeability soil used in a composite liner are referred to as the components of the composite liner. The terms 'geomembrane liner' and 'soil liner' should be reserved for geomembranes and soil layers used alone and should not be used to designate the components of a composite liner. The terms 'geomembrane' and 'soil layer' should be used for the components of a composite liner.

1.3 Lining systems

1.3.1 Definition of lining system

Since no liner is impermeable, leakage control cannot result only from liners. Leakage control, however, can result from a combination of liners and drainage layers, performing complementary functions:

- Liners (which are low-permeability barriers) impede the flow of liquids toward the ground.
- Drainage layers (which have a high permeability) intercept the liquids and convey the flow toward a controlled collection point.

The combination of liners and drainage layers in a containment facility is called a 'lining system'. Therefore, the terms 'liner' and 'lining system' are not synonymous.

1.3.2 Types of lining systems

Double liner. A 'double-liner lining system' simply called a 'double-liner system' or a 'double liner' is a lining system which includes two liners *with a drainage layer to detect, collect, and remove liquids between the two liners* (Fig. 1(c, d, e)). Clearly, two liners in contact (i.e. without an intermediate drainage layer) do not constitute a double liner; they constitute a composite liner, which is a single liner, as discussed below.

Single liner. A single liner is a lining system which includes only one liner (Fig. 1(a, b)). A single liner can be comprised of several components: this is the case of composite liners (defined in Section 1.2.3), which are comprised of a geomembrane on a low-permeability soil, *without* a drainage layer in between.

1.3.3 Terminology related to double liners

The two liners of a double liner are referred to as the *top liner* and the *bottom liner*. (The terminology *primary liner* and *secondary liner* is also

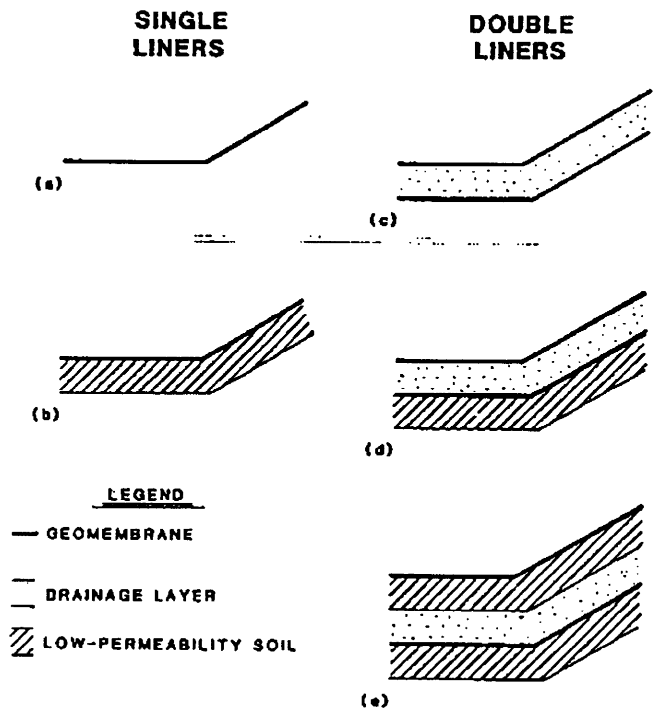

Fig. 1. Five examples of lining systems: (a) single geomembrane liner; (b) single composite liner; (c) double geomembrane liner; (d) double liner with geomembrane top (or primary) liner and composite bottom (or secondary) liner; (e) double composite liner.

used.) The intermediate drainage layer is the *leakage collection layer*. This layer is part of the *leakage detection, collection, and removal system*, which also includes collector pipes and sumps.

1.3:4 Materials used in lining systems

Review of materials. Liner materials were discussed in Section 1.2.2. High-permeability materials used to construct leakage collection layers include:

- high-permeability soils such as sands and gravels, often combined with pipes; and
- synthetic drainage materials (also called synthetic transmission media) such as thick needlepunched nonwoven geotextiles, geonets, geomats and corrugated or waffled plates.

In addition to their use as transmission media, geotextiles are used extensively in lining systems: they are used as filters or separators to prevent contamination of high-permeability materials by fine soils or waste, and they are used as cushions to protect geomembranes from damage by adjacent materials.

Geomembranes, synthetic drainage materials, and geotextiles are all members of a class of products terms *geosynthetics*.

Comment on geotextile cushions. It may seem appropriate to use a geotextile cushion between the geomembrane upper component and the low-permeability soil lower component of a composite liner if the soil contains stones which might damage the geomembrane. Geotextiles typically used as cushions are thick; therefore, their hydraulic transmissivity is not negligible and they can convey liquids laterally within their plane. In a composite liner with leakage through a hole in the geomembrane upper component, lateral flow in the geotextile increases the rate of leakage through the composite liner because it increases the surface area of low-permeability soil exposed to a hydraulic head. It may also increase the leakage rate by establishing a connection between a hole in the geomembrane and cracks in the low-permeability soil layer. Therefore, the engineer faces a dilemma: on the one hand, a geotextile cushion placed between the two components of a composite liner will help to prevent holes in the geomembrane; on the other hand, if there is a hole, the leakage rate may be higher than without a geotextile.

In the vast majority of cases, no geotextile is used between the geomembrane and the low-permeability soil components of a composite liner, because (if the geomembrane is strong and the low-permeability soil does not contain sharp stones) a geotextile cushion is not usually necessary, whereas there is a significant risk of leakage rate increase as a result of the presence of the geotextile. However, test results and discussions presented in this paper show that there may be cases where the presence of the geotextile does not increase the leakage rate due to a hole in the geomembrane; in these cases, the use of a geotextile may be justified. The reader is cautioned, however, that more research is needed before it becomes possible to recommend the use of a geotextile between the geomembrane and the low-permeability soil components of a composite liner.

Of course, if a geotextile cushion is placed between the upper and the lower component of a composite liner, it must not be connected to a sump or any kind of outlet because the geomembrane, the geotextile, and the soil layer would then form a double liner, which is not the goal. In subsequent discussions, we will assume that, in the rare cases where a geotextile would be incorporated in a composite liner, it is not connected to a sump.

1.3.5 Uses of lining systems

Types of containment facilities. Typical examples of lining systems are shown in Fig. 1. Lining systems are used in three types of containment facilities:

- facilities containing liquids such as dams, canals, reservoirs (to which a variety of names are given such as ponds, lagoons, surface impoundments, liquid impoundments);
- facilities containing solids such as landfills, waste piles, and ore leach pads; and
- facilities containing mostly liquids at the beginning of operations and mostly solids at the end, such as settling ponds, evaporation ponds and sludge ponds.

Leachate collection. In facilities containing solids, there is generally a *leachate collection layer* above the top liner. This layer is usually made of high-permeability materials similar to those used to construct leakage collection layers. These materials were described in Section 1.3.4. The purpose of the leachate collection layer is to collect the leachate and convey it toward a sump where it is removed from the facility. The leachate is the liquid that has permeated through the solid contained in the facility (e.g. contaminated liquid that has seeped through the waste stored in a landfill, or pregnant solution in the case of an ore leach pad). The efficiency of the leachate collection layer governs the hydraulic head acting on the top liner of a facility containing solids. The hydraulic head governs the leakage rate through the liner, as discussed in the next section.

1.3.6 Hydraulic head

Definition. Leakage through a liner in contact with a liquid is governed by the hydraulic head difference to which the liner is subjected. Assuming that the liner is saturated, the hydraulic head difference across the liner is given by:

$$\Delta h = h_w + H_L \tag{1}$$

where: Δh = hydraulic head difference; h_w = hydraulic head acting on top of the liner; and H_L = liner thickness.

If the liquid on top of the liner is not flowing (with the exception of the slow movement due to leakage through the liner), the *hydraulic head acting on the liner* is equal to the *depth of liquid on top of the liner*. If the liquid located on top of the liner is flowing laterally (as in a leachate collection layer), the head is different from the depth of liquid. However, in most practical cases the difference between the *hydraulic head acting on the liner* and the *depth of liquid on top of the liner* is negligible and, in this paper, the two expressions will be used interchangeably.

Typical values. Liquid depths on liners (i.e. hydraulic heads acting on liners) are as follows:

- In facilities containing liquids, the top liner (of a double liner) or, simply, the liner (in the case of a single liner) is subjected to the depth of impounded liquid.
- In facilities containing solids there is always some liquid (leachate) in contact with the lin~~er.~~ In these facilit~~ies, the depth~~ of liquid on the *liner exposed to the contained solids* is always designed to be less than a maximum value, typically 0·3 m (1 ft) when a layer of granular soil is used for the leachate collection system, or a few millimeters when a synthetic drainage layer is used for the leachate collection system. (The *liner exposed to the contained solids* is the top liner in the case of a double liner or, simply, the liner in the case of a single liner.) Leachate generation varies significantly over time (e.g. it peaks following a storm); consequently, most of the time, the depth of liquid on the liner exposed to solids is less than the maximum design value.
- In all cases, the bottom liner of a double liner is normally subjected to a very small liquid depth.

In the analyses presented in this paper, some typical liquid depth values will be considered, for the sake of examples or comparisons. Liquid depths of 0·03 m (0·1 ft) and 0·003 m (0·01 ft) will be considered for the bottom liner of a double liner. For the top liner of a double liner, or for the liner in the case of a single liner, the following liquid depths will be considered:

- 30 m (100 ft) for deep facilities containing liquids (such as dams and large water reservoirs);
- 3 m (10 ft) for shallow facilities containing liquids (such as canals, small water reservoirs, storage of industrial liquids, and storage of liquid chemical waste); and
- 0·3 m (1 ft) or 0·003 m (0·01 ft) for facilities containing solids depending on the type of high-permeability material used in the leachate collection layer, granular soil or synthetic drainage layer, respectively.

1.3.7 Uses of composite liners

Composite liners are used to decrease leakage rates and this paper will show that this objective is usually achieved. However, composite liners have two drawbacks that engineers must consider at the conceptual design stage:

- Composite liners must be used with caution in liquid containment facilities. If the geomembrane component of the composite liner is directly in contact with the contained liquid (in other words, if the geomembrane is not covered with a heavy material such as a layer of earth or concrete slabs), and if there is leakage through the geomembrane, liquids will tend to accumulate between the low-permeability soil (which is the lower component of the composite liner) and the geomembrane, since the submerged portion of the geomembrane (whose specific gravity is close to 1) is easily uplifted. Then, if the impoundment is rapidly emptied, the geomembrane will be subjected to severe tensile stresses because the pressure of the entrapped liquids is no longer balanced by the pressure of the impounded liquid. Therefore, a composite liner should always be loaded, which is automatically the case in a landfill or in a waste pile, and which must be taken into account in the design of a liquid containment facility.

- If the top liner of a double-liner system is a composite liner (Fig. 1(e)) the compaction of the soil component of this liner will induce stresses in the underlying materials. These stresses may damage the geosynthetics (geotextile filter and geonet drain) that may be used in the leakage collection layer, and the geomembrane component of the bottom liner. Therefore, the soil component of a top composite liner must be compacted with great care and light equipment, and often will not be as well compacted as the soil component of a bottom composite liner.

In addition to these drawbacks which must be considered at the conceptual design stage, composite liners may have defects as indicated in Section 3.1.2.

1.4 Leakage definition

1.4.1 Definitions: leak and leakage

According to Webster's dictionary:

- A leak is 'a crack or opening that permits something to escape from or enter a container or conduit'.
- Leakage is 'something that escapes by leaking' or 'an amount lost as the result of leaking'.

1.4.2 Leak size and leakage rate

The term 'leak size' designates the size of a hole, expressed as a surface area or dimensions such as a diameter (e.g. a 1 cm^2 leak, a 1 in^2 leak, a 2 mm diameter leak, a 0·25 in diameter leak). The term 'leak size' is sometimes mistakenly used for 'leakage rate', which is the flow rate through a leak or a group of leaks. The leakage rate is expressed as a volume per unit of time (m^3/s, liters/day, gallons/day). The term 'unitized leakage rate' will be used in this paper as an abbreviation for 'leakage rate per unit area of liner', which is expressed as a volume per unit of time per unit of area (m^3/s per m^2 (which is equivalent to m/s), liters/hectares per day (lphd), liters/1000 m^2/day (ltd), gallons/acre/day (gpad)). Unit conversions are given in Table 1. The relationship between unitized leakage rate and leakage rate is as follows:

$$q = Q/A \tag{2}$$

where: q = unitized leakage rate (i.e. leakage rate per unit area of liner); Q = leakage rate; and A = considered area of liner. Basic SI units are: q (m/s), Q (m^3/s), and A (m^2).

TABLE 1
Leakage Rate Units

Leakage rate (Q)	
1 m^3/s	= $8{\cdot}64 \times 10^7$ liters/day
	= $2{\cdot}28 \times 10^7$ gallons/day
1 liter/day	= $1{\cdot}16 \times 10^{-8}$ m^3/s
	= 0·26 gallon/day
1 gallon/day	= $4{\cdot}38 \times 10^{-8}$ m^3/s
	= 3·78 liters/day
Unitized leakage rate (q)	
1 m/s	= $8{\cdot}64 \times 10^{10}$ liters/1 000 m^2 per day
	= $8{\cdot}64 \times 10^{11}$ liters/ha per day
	= $9{\cdot}24 \times 10^{10}$ gallons/acre per day
1 liter/ha/day	= $1{\cdot}16 \times 10^{-12}$ m/s
	= 0·107 gallon/acre per day
	= 0·1 liters/1 000 m^2 per day
1 liter/1 000 m^2/day	= $1{\cdot}16 \times 10^{-11}$ m/s
	= 1·07 gallon/acre per day
	= 10 liters/ha per day
1 gallon/acre/day	= $1{\cdot}08 \times 10^{-11}$ m/s
	= 9·35 liters/ha per day
	= 0·935 liters/1 000 m^2 per day

From a practical standpoint, the following approximate conversions can be used:

1 lphd ≈ 0·1 gpad
1 gpad ≈ 10 lphd
1 ltd ≈ 1 gpad

where: lphd = liter/ha per day, ltd = liter/1 000 m^2 per day, gpad = gallon/acre per day.

Notes: 1 hectare = 100 m × 100 m = 10 000 m^2 = 2·47 acres. 1 acre = 55 yd × 88 yd = 4 840 yd^2 = 43 560 ft^2 = 4 047 m^2 = 0·4 ha. The term 'unitized leakage rate' is used as an abbreviation for 'leakage rate per unit area of liner'. Note that the SI unit for unitized leakage rate (m/s) results from m^3/s per m^2.

1.4.3 Darcy's equation

In this paper, reference is often made to Darcy's equation which governs the flow of liquids through porous media such as soils:

$$Q/A = ki = k\Delta h/T \quad (3)$$

where: Q = flow rate (i.e. leakage rate if the considered flow is through a liner); A = area perpendicular to the flow; k = hydraulic conductivity of the porous medium; i = hydraulic gadient; Δh = hydraulic head difference; and T = thickness of the porous medium. Basic SI units are: Q (m^3/s), A (m^2), k (m/s), Δh (m), and T (m); i is dimensionless.

In the case of laminar flow of water through porous media, the hydraulic conductivity, k, is a constant which depends only on the porous medium, the liquid and the temperature (in other words, k is independent of the liquid pressure and the hydraulic gradient). Flow is laminar if the openings of the porous medium are small, which is the case of pea gravel and all finer soils, and needlepunched nonwoven geotextiles. Flow is nonlaminar (turbulent or in the transition between laminar and turbulent) in clean gravel and all coarser materials, and in geosynthetics with large openings such as geonets, geomats and waffled structures. If Darcy's equation is used to express flow rate in materials where the flow is not laminar, k is not a constant, but depends on the hydraulic gradient.

Geomembranes are not porous media like soils and, therefore, flow of liquids through geomembranes is not governed by Darcy's equation. This is why the terminology 'permeation through geomembranes' (see Section 2.2) is preferred to the terminology 'permeability of geomembranes', the term 'permeability' being traditionally associated with porous media. However, for the sake of comparison with soils, the flow of water through geomembranes can be expressed using Darcy's equation, which leads to a value of k that is not a constant, but depends on the pressure of the liquid (and, therefore, the hydraulic gradient). Such a value of k can be called the 'equivalent hydraulic conductivity of the geomembrane for the considered hydraulic gradient (or pressure)'.

2 LEAKAGE THROUGH GEOMEMBRANE LINERS

2.1 Introduction

2.1.1 Scope of the section

As indicated in Section 1.2.4, two types of liners are considered: geomembrane liners (i.e. geomembranes alone) and composite liners (i.e. liners comprised of a geomembrane associated with a layer of low-permeability soil). Section 2 discusses leakage through geomembrane liners. Leakage through composite liners will be discussed in Section 3.

Some of the information presented in Section 2 will be used in Section 3 since the first step of leakage through a composite liner is leakage through the geomembrane component of the composite liner.

2.1.2 Organization of the section
Leakage through a geomembrane can occur as a result of: (i) permeation through an intact geomembrane; and (ii) flow through defects in a geomembrane. Accordingly, leakage due to permeation will be discussed first (Section 2.2), followed by leakage due to geomembrane defects (Section 2.3).

Finally, conclusions regarding leakage through geomembrane liners will be presented in Section 2.4.

2.2 Leakage due to permeation through geomembranes

2.2.1 Limitation of the scope
The following discussion of permeation through geomembranes is primarily concerned with water as the permeant. It is well known that certain organic chemicals permeate geomembranes much more quickly than water. The significance of this fact is addressed in Section 2.2.10.

2.2.2 Liquid permeameter tests
Tests were conducted at the University of Grenoble (France), first by Giroud from 1973 to 1978, and then by Gourc and Faure, using a constant-head, fixed wall permeameter similar to fixed-wall cells sometimes used to measure soil permeability (Fig. 2). (Hereafter, these tests are referred to as 'liquid permeameter tests' to prevent any confusion with other types of permeameter tests used to evaluate permeation by gases or vapors.) These tests have shown that water passes through a geomembrane when there is water on both sides of the geomembrane and the water pressure on one side is different from the water pressure on the other side. Results of these tests were published by Giroud.[2,3] In these publications, Darcy's equation was used as follows to interpret the test results and calculate equivalent hydraulic conductivities:

$$q_g = Q_g/A = k_g i = k_g \Delta h/T_g \tag{4}$$

where: q_g = unitized leakage rate (i.e. leakage rate per unit area of geomembrane) due to geomembrane permeation; Q_g = leakage rate due to geomembrane permeation; A = surface area of the considered geomembrane; k_g = equivalent hydraulic conductivity of the geomem-

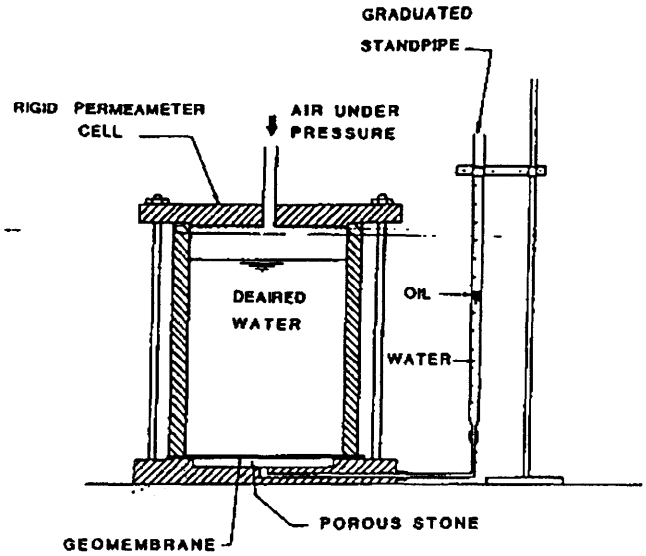

Fig. 2. Liquid permeameter test. The apparatus schematically shown above was used to evaluate water permeation through intact geomembranes at the University of Grenoble (France). Oil is used to prevent evaporation.

brane; i = hydraulic gradient; Δh = hydraulic head difference; and T_g = geomembrane thickness. Basic SI units are: q_g (m/s), Q_g (m^3/s), A (m^2), k_g (m/s), and Δh (m); i is dimensionless.

The equivalent hydraulic conductivities thus calculated vary with the water pressure (and, consequently, the hydraulic head and the hydraulic gradient), which indicates that permeation of water through a geomembrane is different from laminar flow through porous media (where the hydraulic conductivity is constant as discussed in Section 1.4.3). Also, as shown by Giroud,[2,3] the variation of geomembrane equivalent hydraulic conductivity with water pressure is very complex. It is therefore impractical to use equivalent hydraulic conductivities for geomembranes and another approach has been developed, as discussed below.

2.2.3 The concept of coefficient of migration

The liquid permeameter tests discussed above can be interpreted using a *coefficient of migration* defined as follows:

$$q_g = Q_g/A = m_g/T_g \tag{5}$$

where: q_g = unitized leakage rate (i.e. leakage rate per unit area of geomembrane) due to geomembrane permeation; Q_g = leakage rate due to geomembrane permeation; A = surface area of the considered geomembrane; m_g = coefficient of migration of the geomembrane; and T_g = geomembrane thickness. Basic SI units are: q_g (m/s), Q_g (m³/s), A (m²), m_g (m²/s), and T_g (m).

Comparing eqns (4) and (5) leads to the following relationship between k_g and m_g:

$$m_g = k_g \Delta h \tag{6}$$

There is no fundamental reason to prefer m_g or k_g. The use of m_g is recommended by the authors for the practical reasons discussed below.

The geomembrane coefficient of migration, m_g, varies with the water pressure (and, therefore, the hydraulic head and the hydraulic gradient), but in a way that seems simpler than the way the geomembrane equivalent hydraulic conductivity, k_g, varies. Therefore, for geomembranes, the use of the coefficient of migration seems more practical than the use of the equivalent hydraulic conductivity. In addition, when the term *geomembrane equivalent hydraulic conductivity* is used, there is a connotation that flow is due to advection through pores in the geomembrane. However, the actual mechanism of water migration through the geomembrane is different from pure advection. With the term *geomembrane coefficient of migration*, there is no implied assumption regarding the nature of the migration mechanism.

Values of the coefficient of migration obtained for various geomembranes using the liquid permeameter test results are given in Table 2. Although there are not enough data to draw firm conclusions, it appears that the coefficient of migration increases to some maximum value, m_{gmax}, as the liquid pressure increases. From available data, it appears that the coefficient of migration reaches a plateau $m_g = m_{gmax}$ for liquid pressure of the order of 50–100 kPa (7–14 psi) (i.e. hydraulic heads of the order of 5–10 m (15–30 ft)). The value of m_{gmax}, like the value of m_g, depends on the polymer used to make the geomembrane. (Note: The existence and value of m_{gmax} are tentative due to the difficulty in performing permeameter tests at high pressures and the potential for testing error. Even under high pressures, the flow rates are very small, while the high pressures could cause expansion of the hydraulic system or small amounts of leakage.)

When there is water on both sides of a geomembrane, there cannot be any flow if there is no pressure difference across the geomembrane. Therefore, eqn (6) shows that the coefficient of migration, m_g, must be equal to zero when there is no pressure difference across the geomembrane ($\Delta p = 0$, i.e. $\Delta h = 0$). Consequently, the first part of the curve of the coefficient of migration versus the pressure difference, Δp, increases

TABLE 2
Results of Liquid Permeameter Tests

Geomembrane type	*Pressure difference, Δp (kPa)* 50	100	250	500	750	1000
CSPE		3.8×10^{-12}		5.0×10^{-12}		5.5×10^{-12}
Butyl		7.7×10^{-12}		3.9×10^{-12}		3.1×10^{-12}
Butyl	3.5×10^{-15}	1.7×10^{-13}	1.9×10^{-12}	2.9×10^{-13}		3.0×10^{-13}
EPDM		1.1×10^{-12}		2.3×10^{-12}		2.2×10^{-12}
PVC		1.7×10^{-12}		2.5×10^{-12}		1.1×10^{-12}
PVC		1.6×10^{-12}		2.1×10^{-12}		4.4×10^{-13}
PVC		8.1×10^{-13}		2.0×10^{-12}		1.0×10^{-12}
Asphaltic	4.2×10^{-13}	7.4×10^{-13}	6.7×10^{-13}	6.5×10^{-13}	7.4×10^{-13}	
Asphaltic		1.6×10^{-13}	3.2×10^{-13}	6.5×10^{-13}	4.5×10^{-13}	
		Values of the migration coefficient, m_g (m^2/s)				

Note: Values of geomembrane migration coefficients (m_g) were obtained from tests conducted at the University of Grenoble (France) with the apparatus shown in Fig. 2.

TABLE 3
Results of Water Vapor Transmission Tests on Geomembranes

Polymer	*Geomembrane thickness T_g (mm)*	*Water vapor transmission WVT (g/(m^2. day))*	*Coefficient of migration m_g (m^2/s)*	*Equivalent hydraulic conductivity k_g (m/s)*
Butyl rubber	0·85	0·384	3.8×10^{-15}	2.7×10^{-14}
	0·85	0·020	2.0×10^{-16}	1.4×10^{-15}
	1·85	0·097	2.1×10^{-15}	1.5×10^{-14}
CPE	0·53	0·643	3.9×10^{-15}	2.8×10^{-14}
	0·79	1·400	1.3×10^{-14}	9.0×10^{-14}
	0·79	0·320	2.9×10^{-15}	2.1×10^{-14}
	0·85	0·264	2.6×10^{-15}	1.8×10^{-14}
	0·94	0·305	3.3×10^{-15}	2.3×10^{-14}
	0·97	0·643	7.2×10^{-15}	5.1×10^{-14}
CSPE	0·74	0·333	2.9×10^{-15}	2.0×10^{-14}
	0·76	0·663	5.8×10^{-15}	4.1×10^{-14}
	0·89	0·438	4.5×10^{-15}	3.2×10^{-14}
	0·91	0·748	7.9×10^{-15}	5.5×10^{-14}
	0·94	0·422	4.6×10^{-15}	3.2×10^{-14}
	1·07	0·252	3.1×10^{-15}	2.2×10^{-14}
Elasticized polyolefin	0·72	0·142	1.2×10^{-15}	8.3×10^{-15}
CO	1·160	20·18	2.7×10^{-13}	1.9×10^{-12}
	1·650	14·30	2.7×10^{-13}	1.9×10^{-12}

TABLE 3—*contd.*

Polymer	*Geomembrane thickness* T_g *(mm)*	*Water vapor transmission* *WVT* *(g/(m² . day))*	*Coefficient of migration* m_g *(m²/s)*	*Equivalent hydraulic conductivity* k_g *(m/s)*
EPDM	0·51	0·270	$1{\cdot}6 \times 10^{-15}$	$1{\cdot}1 \times 10^{-14}$
	0·94	0·190	$2{\cdot}1 \times 10^{-15}$	$1{\cdot}5 \times 10^{-14}$
	1·70	0·172	$3{\cdot}4 \times 10^{-15}$	$2{\cdot}4 \times 10^{-14}$
Neoprene	0·51	0·304	$1{\cdot}8 \times 10^{-15}$	$1{\cdot}3 \times 10^{-14}$
	0·91	0·473	$5{\cdot}0 \times 10^{-15}$	$3{\cdot}5 \times 10^{-14}$
	1·27	0·429	$6{\cdot}3 \times 10^{-15}$	$4{\cdot}4 \times 10^{-14}$
	1·59	0·237	$4{\cdot}4 \times 10^{-15}$	$3{\cdot}1 \times 10^{-14}$
Nitrile rubber	0·76	5·51	$4{\cdot}8 \times 10^{-14}$	$3{\cdot}4 \times 10^{-13}$
Polybutylene	0·69	0·084	$6{\cdot}7 \times 10^{-16}$	$4{\cdot}7 \times 10^{-15}$
Polyester elastomer	0·20	10·50	$2{\cdot}4 \times 10^{-14}$	$1{\cdot}7 \times 10^{-13}$
LDPE	0·76	0·057 3	$5{\cdot}1 \times 10^{-16}$	$3{\cdot}5 \times 10^{-15}$
HDPE	0·80	0·017 2	$1{\cdot}6 \times 10^{-16}$	$1{\cdot}1 \times 10^{-15}$
	2·44	0·006 2	$1{\cdot}8 \times 10^{-16}$	$1{\cdot}2 \times 10^{-15}$
HDPE-alloy	0·86	0·047 2	$4{\cdot}7 \times 10^{-16}$	$3{\cdot}3 \times 10^{-15}$
PVC	0·28	4·42	$1{\cdot}4 \times 10^{-14}$	$1{\cdot}0 \times 10^{-13}$
	0·51	2·97	$1{\cdot}8 \times 10^{-14}$	$1{\cdot}2 \times 10^{-13}$
	0·76	1·94	$1{\cdot}7 \times 10^{-14}$	$1{\cdot}2 \times 10^{-13}$
	0·79	1·85	$1{\cdot}7 \times 10^{-14}$	$1{\cdot}2 \times 10^{-13}$
PVC-E	0·91	2·78	$2{\cdot}9 \times 10^{-14}$	$2{\cdot}1 \times 10^{-13}$
PVC-OR	0·83	4·17	$4{\cdot}0 \times 10^{-14}$	$2{\cdot}8 \times 10^{-13}$
Saran film	0·013	0·563	$8{\cdot}5 \times 10^{-17}$	$5{\cdot}9 \times 10^{-16}$

Notes: The water vapor transmission (WVT) rates are from Haxo *et al.*[5] From these WVT values, the values of the coefficient of migration (m_g) were derived using eqn (18) and the values of the equivalent hydraulic conductivity (k_g) were derived using eqn (15). (See also Table 4.) All these tests were conducted at 23°C with a relative humidity difference of 50%, which is equivalent to a vapor pressure difference, Δp, of 1·4 kPa (0·2 psi). Definitions of polymer symbols can be found in Refs 1 and 2.

from zero to m_{gmax} as the pressure difference increases from zero to a value, $\Delta p_{plateau}$, approximately equal to 50–100 kPa (7–14 psi).

2.2.4 Water vapor transmission tests

It is difficult to conduct water permeameter tests on geomembranes with a head of water smaller than 5 m (16 ft) (i.e. a pressure smaller than 50 kPa (7 psi)) because the rates of water permeation are too small to be accurately measured. As indicated in Section 1.3.6, hydraulic heads acting on liners are often smaller than 5 m (16 ft). Therefore, it is useful to complement results from the liquid permeameter tests cited above with results from water vapor transmission tests. These tests are typically conducted with a vapor pressure difference across the geomembrane of the order of 1–10 kPa (0·15–1·5 psi).

Water vapor transmission tests have been extensively used on various types of membranes and the test procedures have been standardized (e.g. ASTM E96). In brief, the test is performed as follows: the two sides of a geomembrane specimen are subjected to two different relative humidities. Typically, one side is subjected to a 50% relative humidity while the other side is maintained at 0% relative humidity (using a desiccant) or 100% relative humidity (by having liquid water (at nearly zero pressure) in contact with the entire surface of the geomembrane specimen). The relative humidity difference corresponds to a vapor pressure difference which drives vapor through the geomembrane. The relationship between vapor pressure and relative humidity is as follows:

$$p = p_s H \tag{7}$$

where: p = vapor pressure; p_s = vapor pressure at the saturation point (which is a function of temperature and is tabulated in most physics handbooks); and H = relative humidity. Basic SI units are: p (Pa) and p_s (Pa); H is dimensionless.

The water vapor transmission rate (WVT) measured in the test is *the mass of vapor permeating the geomembrane per unit area of geomembrane per unit period of time*. The SI unit is kg/(m^2 s) and test results are often reported in g/(m^2 day). (Note: 1 g/(m^2 day) = $1{\cdot}16 \times 10^{-8}$ kg/(m^2 s).)

Results from water vapor transmission tests are given in Tables 3 and 4.

2.2.5 *Fick's equation*

Water vapor transmission tests are usually interpreted using Fick's equation:

$$\mathrm{WVT} = \frac{M}{At} = D_g \Delta p / T_g \tag{8}$$

where: WVT = water vapor transmission rate; M = mass of vapor migrating through the geomembrane; A = geomembrane surface area; t = time (i.e. duration of permeation); D_g = water vapor diffusion coefficient of the geomembrane; Δp = vapor pressure difference between the two sides of the geomembrane; and T_g = geomembrane thickness. Basic SI units are: WVT (kg/(m^2 s)), M (kg), A (m^2), t (s), D_g (s), Δp (Pa), and T_g (m).

TABLE 4
Results of Water Vapor Transmission Tests on Polymers

Geomembrane type	*Vapor pressure difference* Δp *(kPa)*	*Water vapor transmission WVT* *(g/(m² day))*	*Reference thickness* T *(mm)*	*Coefficient of migration* m_g *(m²/s)*	*Equivalent hydraulic conductivity* k_g *(m/s)*
CSPE	6·4	161	0·025	$4{\cdot}7 \times 10^{-14}$	$7{\cdot}2 \times 10^{-14}$
Butyl	6·4	26	0·025	$7{\cdot}5 \times 10^{-15}$	$1{\cdot}2 \times 10^{-14}$
PVC	6·1	32	0·025	$9{\cdot}3 \times 10^{-15}$	$1{\cdot}5 \times 10^{-14}$
HDPE 0·92	6·4	28	0·025	$8{\cdot}1 \times 10^{-15}$	$1{\cdot}2 \times 10^{-14}$
0·94	5·8	14	0·025	$4{\cdot}1 \times 10^{-15}$	$6{\cdot}9 \times 10^{-15}$
0·95	6·1	6·7	0·025	$1{\cdot}9 \times 10^{-15}$	$3{\cdot}1 \times 10^{-15}$
0·96	5·8	4	0·025	$1{\cdot}2 \times 10^{-15}$	$2{\cdot}0 \times 10^{-15}$

Notes: The pressure difference, Δp, was derived from the test relative humidity difference using eqn (7). Values ranging from 0·92 to 0·96 are HDPE specific gravities. The water vapor transmission (WVT) rates are from Rogers.[17] From these WVT values, the values of the coefficient of migration (m_g) were derived using eqn (18), and the values of the equivalent hydraulic conductivity (k_g) were derived using eqn (15). (See also Table 3.)

Combining eqns (7) and (8) leads to the following expression for Fick's equation:

$$\mathrm{WVT} = \frac{M}{At} = D_g p_s \Delta H / T_g \tag{9}$$

where: ΔH = relative humidity difference between the two sides of the geomembrane.

Inspection of Fick's equation shows that the water vapor transmission rate (WVT) depends on the pressure used in the test. It also depends on the thickness of the geomembrane and therefore characterizes a given geomembrane (e.g. a 1·5 mm (60 mil) thick HDPE geomembrane), not a geomembrane material (e.g. HDPE). Consequently, *water vapor transmission rates (WVT) are meaningful only if the vapor pressure and the geomembrane thickness used in the test are known*. Values of WVT given in the literature should therefore be used with caution.

Knowing the water vapor transmission rate of a given geomembrane specimen obtained in a given test, the quantity of vapor permeating through a geomembrane made with the same material can be calculated for different pressures and thicknesses using the following relationships derived from Fick's equation:

$$\frac{M}{At} = \mathrm{WVT} = (\mathrm{WVT})_o \frac{\Delta p}{\Delta p_o} \frac{T_{go}}{F_g} = (\mathrm{WVT})_o \frac{\Delta H}{\Delta H_o} \frac{T_{go}}{T_g} \tag{10}$$

where: M = mass of vapor migrating through the considered geomembrane when it is subjected to a pressure difference Δp; A = considered geomembrane surface area; t = time (i.e. duration of permeation through the considered geomembrane); WVT = water vapor transmission rate through the considered geomembrane when it is subjected to a pressure difference Δp; $(\mathrm{WVT})_o$ = water vapor transmission rate through the geomembrane specimen used in the test; Δp = vapor pressure difference between the two sides of the considered geomembrane; Δp_o = vapor pressure difference between the two sides of the geomembrane used in the water vapor transmission test; T_{go} = thickness of the geomembrane specimen used in the water vapor transmission test; T_g = thickness of the considered geomembrane; ΔH = relative humidity difference between the two sides of the considered geomembrane; and ΔH_o = relative humidity difference between the two sides of the geomembrane specimen used in the water vapor transmission test. Basic SI units are: M (kg), A (m^2), t (s), WVT (kg/(m^{2}s)), Δp (Pa), Δp_o (Pa), T_{go} (m) and T_g (m); ΔH and ΔH_o are dimensionless.

It should be pointed out that the use of eqn (10) should be restricted to pressures that are not too different from the pressures typically used to conduct the water vapor transmission test (e.g. pressures of the order of 1–10 kPa (0·15–1·5 psi).

2.2.6 Discussion of Fick's equation

The first expression of Fick's equation (eqn (8)), shows that there is *no vapor transmission* through a geomembrane if there is *no vapor pressure* difference between the two sides of the geomembrane. According to the second expression of Fick's equation (eqn (9)), it is equivalent to say that there is no vapor transmission through a geomembrane if the relative humidity is the same on both sides of the geomembrane. This happens in particular when there is liquid on both sides of the geomembrane (H = 100%). Therefore, if there is liquid on both sides of a geomembrane, there is no vapor transmission through the geomembrane, even if there is a pressure difference between the two sides.

From these facts, some researchers have concluded that there is no liquid migration at all through a geomembrane if there is liquid on both sides of the geomembrane, regardless of the pressure difference; in other words, they have concluded that vapor transmission is the only mechanism of fluid transport through a geomembrane. However, it seems that another conclusion can be drawn as a result of the following rationale:

- As indicated above, there is no vapor transmission through a geomembrane exposed to liquid on both sides.
- The liquid permeameter tests discussed in Section 2.2.2 show that liquid does migrate through a geomembrane when there is liquid on both sides, with a pressure difference.
- Therefore, vapor transmission is not the only mechanism of water migration through a geomembrane.

The fact that there is water migration through a geomembrane when there is water (in liquid state) on both sides, with a pressure difference, does not necessarily imply that liquid is flowing through small channels in geomembranes as it does in soils. It is more likely that water transport through geomembranes is at the molecular level because spaces between the molecular chains of the polymers used to manufacture geomembranes are extremely narrow. It is even possible that the mechanism of water migration through geomembranes at the molecular level is identical whether the cause of migration is a liquid pressure difference or a vapor pressure difference. Clearly, additional research on flow through geomembranes would be useful to define the transport mechanisms better.

2.2.7 Relationship between liquid and vapor migrations

Two types of tests have been discussed above:

- *Liquid permeameter tests*. In these tests, the driving pressure causing water migration through the geomembrane is liquid pressure difference. For practical reasons, these tests are typically conducted with relatively high pressures.
- *Water vapor transmission tests*. In these tests, the driving pressure causing water migration through the geomembrane is vapor pressure difference. For practical reasons, these tests are typically conducted with relatively low pressures.

Since their pressure ranges are different, these two types of tests are complementary. However, to compare the results from these two types of tests, the results must be expressed in the same way. It is therefore necessary to establish relationships between the coefficients used to express the results of liquid permeameter tests, on the one hand, and water vapor transmission tests, on the other hand. This is achieved by establishing a relationship between Darcy's equation, used to interpret liquid permeameter tests (eqn (4)), and Fick's equation, used to interpret water vapor transmission tests (eqn (8)).

Darcy's equation and Fick's equation are similar. Both equations incorporate coefficients of proportionality (equivalent hydraulic conductivity in Darcy's equation, k_g, and vapor diffusion coefficient in Fick's equation, D_g) relating the same two fundamental physical quantities: the rate of mass transport and the pressure difference. Therefore, a relationship can be established between the two coefficients of proportionality, k_g and D_g. The relationship will correspond to a physical reality if the mechanism of water transport through a geomembrane at the molecular scale is the same regardless of the cause of water migration, liquid pressure or vapor pressure, as suggested in Section 2.2.6. At a minimum, the relationship is a useful tool to compare rates of water mass transport measured using tests where the nature of the driving pressure is different, such as the liquid permeameter test described in Section 2.2.2 and the water vapor transmission test described in Section 2.2.4.

A preliminary step in the establishment of the relationship between k_g and D_g is to rewrite Darcy's equation by: (i) expressing the flow rate as a function of the mass transport rate; and (ii) expressing the liquid head difference as a function of the pressure difference.

The flow rate, Q, in Darcy's equation, is in fact a rate of volume transport. It can be converted into a rate of mass transport using the following equation:

$$Q = (M/t)/\rho \tag{11}$$

where: Q = flow rate; M/t = mass transport rate; M = mass; t = time; and ρ = density of the considered fluid (typically water) in the liquid phase. Basic SI units are: Q (m^3/s), M/t (kg/s), M (kg), t (s), and ρ (kg/m^3).

The liquid head difference, Δh, in Darcy's equation can be converted into a pressure difference using the following equation:

$$\Delta h = \Delta p/(\rho g) \tag{12}$$

where: Δh = liquid head difference across the geomembrane; Δp = pressure difference across the geomembrane; ρ = density of the considered liquid (usually water); and g = acceleration due to gravity. Basic SI units are: Δh (m), Δp (Pa), ρ (kg/m^3), and g (m/s^2).

Substitution of eqns (11) and (12) in eqn (4) (which is the traditional expression of Darcy's equation with flow rate and hydraulic head difference) yields a new expression of Darcy's equation with the mass transport rate and the pressure difference:

$$\frac{M}{t} = k_g \frac{\Delta p}{g T_g} A \tag{13}$$

where: M/t = mass transport rate; k_g = geomembrane equivalent hydraulic conductivity; Δp = pressure difference; A = geomembrane surface area; g = acceleration due to gravity; and T_g = geomembrane thickness. Basis SI units are: M/t (kg/s), k_g (m/s), Δp (Pa), A (m^2), g (m/s^2), and T_g (m).

Comparing Darcy's equation (eqn (13)) and Fick's equation (eqn (8)) yields:

$$k_g = gD_g \tag{14}$$

where: k_g = geomembrane equivalent hydraulic conductivity (from Darcy's equation); g = acceleration due to gravity; and D_g = geomembrane water vapor diffusion coefficient (from Fick's equation). Basic SI units are: k_g (m/s), g (m/s^2), and D_g (s).

From this important relationship, it is possible to derive relationships between WVT (a coefficient more often used than D_g for water vapor transmission tests), on the one hand, and k_g and m_g (coefficients used for liquid permeameter tests), on the other.

By combining eqns (8) and (14):

$$\mathrm{WVT} = \Delta p k_g/(gT_g) \tag{15}$$

By combining eqns (9) and (14):

$$\mathrm{WVT} = p_s \Delta H k_g/(gT_g) \tag{16}$$

By combining eqns (12) and (15):

$$\mathrm{WVT} = \rho k_g \Delta h/T_g \tag{17}$$

By combining eqns (6) and (17):

$$\mathrm{WVT} = \rho m_g/T_g \tag{18}$$

where: k_g = geomembrane equivalent hydraulic conductivity; g = acceleration due to gravity; T_g = geomembrane thickness; WVT = geomembrane water vapor transmission rate; Δp = pressure difference; p_s = vapor pressure at the saturation point (which is a function of temperature and is tabulated in most physics handbooks); ΔH = relative humidity difference; ρ = liquid density; Δh = hydraulic head difference; and m_g = geomembrane coefficient of migration. Basic SI units are: k_g (m/s), g (m/s^2), T_g (m), WVT (kg/(m^2 s)), Δp (Pa), p_s (Pa), ρ (kg/m^3), Δh (m), and m_g (m^2/s); ΔH is dimensionless.

2.2.8 *Curves of coefficient of migration*

Using the relationships established in Section 2.2.7, it is possible to express the results of the liquid permeameter tests and vapor transmission tests with the same coefficient. Any of the coefficients (k_g, m_g, D_g or WVT) can be used. The use of m_g is preferred for the reasons already indicated in Section 2.2.3: (i) m_g varies with liquid pressure in a simple way; and (ii) m_g is a new coefficient which has not been associated historically with any fluid transport mechanism, and its neutral meaning does not imply any assumption regarding the transport mechanism. In addition, for interpretation of vapor transmission test results, m_g is not dependent on geomembrane thickness as is WVT.

Using eqn (18), the measured water vapor transmission rate (WVT) values given in Tables 3 and 4 have been converted into values of the coefficient of migration. (Tables 3 and 4 also include values of equivalent hydraulic conductivities obtained using eqn (15).) It is interesting to see in Table 3 that the series of tests on a given product (e.g. the series of four tests on PVC) with various thicknesses give consistent values of the coefficient of migration. However, Tables 2, 3 and 4 contain discrepancies and apparently erratic results due to the difficulty of the tests and the sometimes great differences between geomembranes of the same generic type. For example, the large discrepancy between water vapor transmission rates measured on PVC at a 1·4 kPa (0·2 psi) pressure difference (Table 3) and a 6 kPa (0·9 psi) pressure difference (Table 4) probably results from the fact that the PVC tested at a 1·4 kPa (0·2 psi) pressure difference was a geomembrane made of plasticized PVC and the PVC tested at a 6 kPa (0·9 psi) pressure difference was pure PVC. Plasticizers cause PVC to swell, thereby making plasticized PVC more permeable than pure PVC.

There are insufficient data in Tables 2, 3 and 4 to establish a complete table of values of coefficient of migration, m_g, for geomembranes. Systematic testing should be undertaken to investigate the relationship between the coefficient of migration and the pressure difference. In the meantime, we propose to use available data (presented in Tables 2, 3 and 4) to draw curves such as those in Fig. 3. Since we have shown in Section 2.2.3 that $m_g = 0$ when $\Delta p = 0$, it is possible to interpolate between ($m_g = 0$, $\Delta p = 0$) and known data points to obtain m_g for small values of Δp.

From the curves given in Fig. 3 in logarithmic scale, it is possible to draw the curve given in Fig. 4 which illustrates what seems to be the shape of the coefficient of migration–pressure difference curve as can be established from available results. As shown in Fig. 4, the following equations can be proposed:

$$m_g = C_1 \Delta p^n \quad \text{if } \Delta p < \Delta p_{\text{plateau}} \tag{19}$$

$$m_g = m_{g\max} \quad \text{if } \Delta p > \Delta p_{\text{plateau}} \tag{20}$$

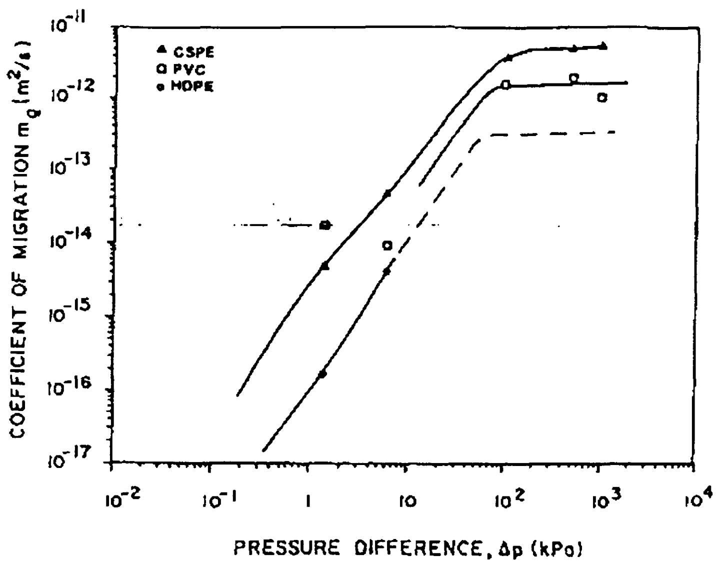

Fig. 3. Coefficients of migration for various geomembranes. The curves show the variation of the coefficient of migration, m_g, as a function of the fluid (vapor or liquid) pressure difference, Δp, across the geomembrane. The data points are from Tables 2, 3 and 4. HDPE geomembranes are generally considered to be less permeable to water than others and this seems to be confirmed by the above curves. The curves also seem to indicate that PVC geomembranes are less permeable to water than CSPE geomembranes. This may not be true in many cases because of the large variety of PVC and CSPE geomembranes: a CSPE geomembrane typically contains 45% CSPE and 55% additives, and a PVC geomembrane typically contains 65% PVC and 35% plasticizers. In contrast, HDPE geomembranes are less variable, because they are essentially made of HDPE with only a very small percentage of additives; therefore, results for HDPE geomembranes are expected to form a smooth curve with no significant scattering. Unfortunately, the database for HDPE geomembranes is limited and the dashed portion of the curve related to HDPE was assumed.

where: m_g = geomembrane coefficient of migration; C_1 = coefficient; Δp = pressure difference; and n = dimensionless coefficient between 1·5 and 2. Basic SI units are: m_g (m^2/s), C_1 ($m^4\,kg^{-2}\,s^3$ if $n = 2$, or $m^{3.5}\,kg^{-1.5}\,s^2$ if $n = 1.5$), and Δp (Pa). Equation (19) assumes that the first part of the curves in Fig. 3 (logarithmic scale) are straight lines.

It is clear from the above discussions that a lot of work needs to be done before it becomes possible to draw firm conclusions on rates of water permeation through geomembranes.

2.2.9 *Example of leakage rate evaluation*

From Fig. 3, or from eqns (19) and (20), with $C_1 = 1 \times 10^{-22}\ m^4\,kg^{-2}\,s^3$, $n = 2$, $\Delta p_{plateau} = 55$ kPa, and $m_{gmax} = 3 \times 10^{-13}\ m^2/s$, it is possible to

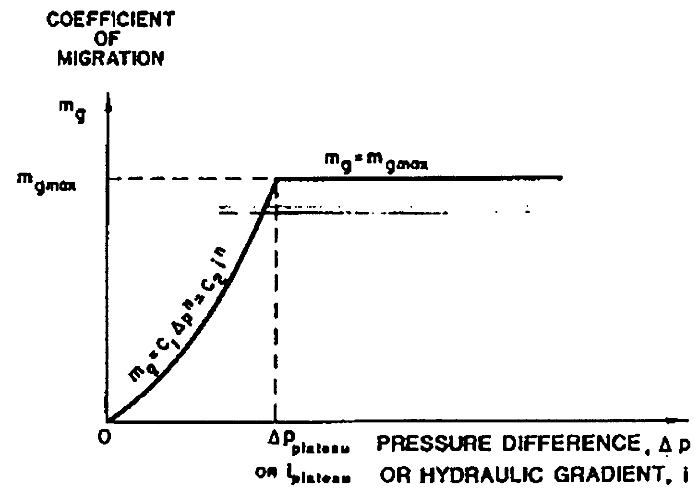

Fig. 4. Schematic shape of the curve giving the coefficient of migration of a geomembrane, m_g, as a function of the pressure difference, Δp. This curve has been established from a limited number of liquid permeameter and water vapor transmission test results and needs to be confirmed by more tests. The exponent n is of the order of 1·5–2; m_{gmax} depends on the geomembrane material; C_1 and C_2 are two constants that depend on the geomembrane material. The value of $\Delta p_{plateau}$ is of the order of 50–100 kPa (7–14 psi), i.e. a hydraulic gradient of the order of 5×10^3 to 1×10^4, if the geomembrane thickness is 1 mm (40 mils), and a hydraulic head of the order of 5–10 m (15–30 ft).

obtain tentative values of the coefficient of migration, m_g, for an HDPE geomembrane, permeated by water. These values are given in the upper part of Table 5. From these coefficients of migration, it is possible to calculate unitized leakage rates due to water permeation through an HDPE geomembrane. This was done using eqn (5) with a geomembrane thickness of 1 mm (40 mils). The tentative unitized leakage rates thus obtained are given in the lower part of Table 5. These tentative unitized leakage rates should only be considered as an example to illustrate the methodology since the coefficient of migration values used for the calculations were assumed (as shown in Fig. 3) from a very limited database.

2.2.10 Migration of chemicals

The liquid permeameter and vapor transmission data in Tables 2, 3 and 4 were from tests using water or water vapor as the permeating fluids. In waste containment applications, the liquid in contact with the geomembrane may be a pure chemical other than water, a mixture of pure chemicals, or a dilute aqueous solution. Most leachates from municipal solid waste landfills and other nonhazardous solid waste containment

TABLE 5
Calculated Unitized Leakage Rates due to Permeation of Water Through an HDPE Geomembrane

	Water depth on top of the geomembrane, h_w					
	0 m (0 ft)	0·003 m (0·01 ft)	0·03 m (0·1 ft)	0·3 m (1 ft)	3 m (10 ft)	>10 m (>30 ft)
Coefficient of migration, m_g (m^2/s)	0	9×10^{-20}	9×10^{-18}	9×10^{-16}	9×10^{-14}	3×10^{-13}
Unitized leakage rate, q_g						
(m/s)	0	9×10^{-17}	9×10^{-15}	9×10^{-13}	9×10^{-11}	3×10^{-10}
(lphd)	0	8×10^{-5}	0·008	0·8	80	260
(gpad)	0	8×10^{-6}	0·0008	0·08	8	28

Notes: These values of utilized leakage rates were calculated using eqn (5) and assuming a geomembrane thickness of 1 mm (40 mils). The coefficients of migration used to calculate the unitized leakage rates in this table were obtained from eqns (19) and (20), with $C_1 = 1 \times 10^{-22}\, m^4\, kg^{-2}\, s^3$, $n = 2$, and $m_{gmax} = 3 \times 10^{-13}\, m^2/s$. The water depths used here correspond to the typical values defined in Section 1.3.6. (To use eqn (19), it is necessary to know the pressure difference, Δp. According to eqn (1), water depths, h_w, are approximately equal to hydraulic head differences, Δh, which are related by eqn (12) to pressure differences, Δp.)

facilities fall into the latter category with relatively low concentrations of a relatively large number of chemical constituents.

Liquid permeameter tests and vapor transmission tests using either pure chemicals, chemical mixtures or aqueous solutions have been reported by August and Tatzky,[4] Haxo *et al.*,[5] Haxo and Waller,[6] Steffen[7] and Telles *et al.*[8] These test results have shown that permeation rates of some organic chemicals through geomembranes are several orders of magnitude larger than the permeation rate of water. The high permeation rates of these chemicals persist even when the organics are completely dissolved in an aqueous solution. Under these conditions, permeation of the aqueous solvent and organic solute are not coupled and the organic solute may permeate the geomembrane to the exclusion of the aqueous solvent. Notwithstanding the high permeation rates measured in laboratory tests, the total chemical mass transport rate in the field may be relatively low, due to the low chemical concentrations in the liquids and leachates contained by many geomembranes (particularly in those solid waste landfills where the primary source of leachate generation is precipitation) and the decay of the initial chemical gradient that exists across the geomembrane (due to the absorption of permeating chemicals by the soil underlying the geomembrane).

Just as permeation of geomembranes by water requires additional research, so does permeation of geomembranes by chemicals. Further consideration of this topic, however, is beyond the scope of this paper.

2.3 Leakage due to defects in geomembranes

2.3.1 Introduction

In addition to leakage due to permeation of liquids through geomembranes (discussed in Section 2.2) there is leakage through geomembrane defects: this subject will be discussed in Section 2.3. As shown in Section 2.2, leakage due to permeation of water can be very small, while it will be shown in this section that leakage due to geomembrane defects can be large.

In the first part of this section, calculations for evaluating leakage rates through geomembrane defects, such as pinholes and holes, will be discussed. The remainder of the section will be devoted to an evaluation of the size and frequency of defects that may occur in a geomembrane. This information is necessary for making analytic calculations of leakage rates through liners (geomembranes alone as well as composite liners). Although all types of defects are considered, the primary focus will be on seam defects because forensic analyses have shown that leakage through geomembrane liners is often due to defective seams, and the most complete documentation of geomembrane defects is for seam defects.

At the end of this section, recommendations are presented regarding appropriate assumptions for the size and frequency of geomembrane defects for lining system design calculations.

2.3.2 Leakage due to pinholes in the geomembrane

Definition of pinholes. According to Giroud[3] pinholes should be distinguished from holes and can be defined as openings having a dimension (such as diameter) significantly smaller than the geomembrane thickness. The primary source of pinholes are manufacturing defects. Early manufacturing techniques for geomembranes often resulted in a significant number of pinholes. However, manufacturing processes and polymer formulations have advanced to a degree that pinholes are now relatively rare.

Basic equation. For leakage calculation purposes, pinholes can be considered as pipes and, therefore, according to Giroud,[3] Poiseuille's equation can be used:

$$Q = \pi \rho g h_w d^4/(128 \eta T_g) \qquad (21)$$

TABLE 6
Calculated Leakage Rates due to Pinholes and Holes in a Geomembrane

		Water depth on top of the geomembrane, h_w				
	Defect diameter	*0·003 m (0·01 ft)*	*0·03 m (0·1 ft)*	*0·3 m (1 ft)*	*3 m (10 ft)*	*30 m (100 ft)*
Pinholes	0·1 mm (0·004 in)	0·006 (0·0015)	0·06 (0·015)	0·6 (0·15)	6 (1·5)	60 (15)
	0·3 mm (0·012 in)	0·5 (0·1)	5 (1)	50 (13)	500 (130)	5 000 (1 300)
Holes[a]	2 mm (0·08 in)	40 (10)	130 (30)	400 (100)	1 300 (300)	4 000 (1 000)
	11·3 mm (0·445 in)	1 300 (300)	4 000 (1 000)	13 000 (3 000)	40 000 (10 000)	130 000 (30 000)
		Values of leakage rate in liters/day (gallons/day)				

Notes: The geomembrane is assumed to be overlain and underlain by a very pervious medium such as coarse gravel or geonet. The leakage rate calculated for holes would be significantly reduced if the pervious medium in contact with the geomembrane on one or both sides is sand or a less permeable material. In the case of pinholes, a geomembrane thickness of 1 mm (40 mils) was used in the calculations, while in the case of holes, leakage rates are independent of geomembrane thickness. Equation (21) was used for pinholes and eqn (22) for holes. The pinhole calculations were based on water at 20°C. The water depths used here correspond to the typical values defined in Section 1.3.6.

[a]The 2·0 mm diameter circular hole ('small hole') has a surface area of 3·1 mm^2 and the 11·3 mm diameter circular hole ('large hole') has a surface area of 1 cm^2. These are the two holes recommended for design in Section 2.3.9.

where: Q = leakage rate through a pinhole; h_w = liquid depth on top of the geomembrane; T_g = thickness of the geomembrane; d = pinhole diameter; ρ and η = density and dynamic viscosity of the liquid, respectively; and g = acceleration due to gravity. Basic SI units are: Q (m^3/s), h_w (m), T_g (m), d (m), ρ (kg/m^3), η (kg/(m s)), and g (m/s^2). For water at 20°C, $\rho = 1000$ kg/m^3 and $\eta = 10^{-3}$ kg/(m s).

The above equation is different from the equation used for evaluating leakage through holes (see eqn (22), Section 2.3.3).

Calculations. Equation (21) has been used to calculate leakage rates for two typical pinhole diameters, 0·1 mm (0·004 in) and 0·3 mm (0·012 in), assuming a geomembrane thickness of 1 mm (40 mils). Results are presented in Table 6. The hydraulic heads used in these calculations are equal to the liquid depths defined in Section 1.3.6.

2.3.3 Leakage due to holes in the geomembrane

Definition of holes. According to Giroud[3] holes should be distinguished from pinholes and can be defined as openings having a dimension (e.g. diameter) about as large as, or larger than, the geomembrane thickness.

Assumption regarding underlying material. Leakage rates through geomembrane holes are significantly affected by the material underlying the geomembrane. Two extreme cases can be considered: a high-permeability material such as a granular or synthetic drainage medium, and a low-permeability soil such as a clay layer placed under a geomembrane to form a composite liner. The case of a composite liner is addressed in Section 3.

In this section, the material underlying the geomembrane is assumed to have an infinite hydraulic conductivity. Tests by Brown *et al.*[9] have shown that underlying soils with a hydraulic conductivity higher than 10^{-3} m/s (10^{-1} cm/s) do not significantly affect free flow through a small geomembrane defect. Their results justify the assumption of an infinite hydraulic conductivity for many drainage materials underlying a geomembrane liner.

Assumption regarding overlying material. Leakage rates through geomembrane holes are affected by the material overlying the geomembrane. For this paper, the authors did not investigate the influence of overlying soil permeability on leakage rate. Evaluation of this influence may be important in some cases and additional work in this area is needed. At least, it is clear that the more permeable the overlying material, the higher the leakage rate for a given hydraulic head. In subsequent calculations, the overlying material will conservatively be assumed to be infinitely pervious. This assumption, which is acceptable if the overlying material is very pervious such as coarse gravel or geonet, may lead to a significant overestimate of the leakage rate if the overlying material is sand or a less permeable material.

Basic equation. Assuming that the considered geomembrane is located between two infinitely pervious media, Bernoulli's equation for free flow through an orifice can be used to evaluate the leakage rate through a hole in the geomembrane:

$$Q = C_B a \sqrt{2gh_w} \tag{22}$$

where: Q = leakage rate through a geomembrane hole; a = hole area; g = acceleration due to gravity; and h_w = liquid depth on top of the geomembrane. C_B is a dimensionless coefficient, valid for any Newtonian fluid, and is related to the shape of the edges of the aperture; for sharp edges, C_B = 0·6. Basic SI units are: Q (m^3/s), a (m^2), g (m/s^2), and h_w (m).

Calculations. Equation (22) has been used to calculate leakage rates for two typical hole sizes:

- a 2·0 mm (0·08 in) diameter hole, assumed to be due to defective seaming (as discussed in Section 2.3.8), that might escape detection by a construction quality assurance program; and
- a 11·3 mm (0·445 in) diameter hole that might result from failure of the geomembrane due to poor design, damage to the geomembrane during placement of overlying materials, etc.

The first hole ('small hole') has an area of 3·1 mm^2 (0·005 in^2) and the second hole ('large hole') has an area of 1 cm^2 (0·16 in^2). Both hole sizes can be considered for design calculations (see Section 2.3.9).

Results from calculations using eqn (22) are given in Table 6. Hydraulic heads considered in these calculations are equal to the liquid depths defined in Section 1.3.6. (Note: When liquid depth on the geomembrane is very small, the flow through an orifice may not be free as a result of surface tensions. The use of eqn (22) for a liquid depth of 0·003 m (0·01 ft) in Table 6 is therefore questionable. However, eqn (22) is used for lack of a better method and to ensure the consistency of comparisons.)

2.3.4 Geomembrane defects

Defects that are likely to occur in geomembranes are numerous and may be caused by a wide variety of factors including improper design, defective manufacturing and defective installation. A number of publications are available which discuss the various types of defects that have been observed in geomembrane-lined units.[2, 10–12]

Typical defects observed in geomembranes include:

- discontinuous or defective seams resulting from fabrication or installation factors including excessive moisture or humidity, improper ambient or seaming temperature, contamination by dust or dirt, and inadequate workmanship or quality assurance;
- seam failures caused by excessive stresses during placement of cover materials or operation of the lined facility;
- damage to geomembranes during construction or facility operation as a result of excessive stresses caused by equipment traffic;
- puncturing of geomembranes by stones in the support or cover material when compressive stresses are applied as a result of equipment traffic or the weight of stored material;
- tensile failure of geomembranes due to excessive stresses generated by the weight of stored material or movements of materials in contact with the lining system;

seaming was provided by the installer, using visual inspection and vacuum box.

Upon completion of the liner installation, the tank was filled with water to check for leaks. The liner did leak, so the tank was emptied, repairs were made and the tank was filled again. This cycle was repeated several times, with leaks found on every filling. Leaks were found at 15 different locations, i.e. an average of one leak per 7 m (23 ft) of seam. Because of the complex geometry of the tank, this incidence of seam defects was probably larger than the incidence which would be experienced in more typical installations. However, the complex geometry of this tank is probably representative of the difficulties encountered in waste disposal units, dams, or other facilities at the connections between geomembranes and appurtenances such as pipe penetrations, sumps, manholes, intake towers, spillways, etc.

Large surface impoundment. The following case history is reported by Giroud and Fluet.[16] A large reservoir, lined with a single reinforced 1 mm (40 mil) thick chlorosulfonated polyethylene (CSPE-R) geomembrane, had been constructed to contain phosphoric acid. The reservoir was approximately 3 m (10 ft) deep and its surface area was approximately 20 000 m^2 (200 000 ft^2).

One year after the first filling, the reservoir suddenly emptied. The analysis of the failure indicated that phosphoric acid, leaking through several defective seams, attacked the ground, thereby creating cavities. The largest cavity was 1 m (3 ft) in diameter and 0·5 m (20 in) deep. Under the pressure of the impounded liquid, the geomembrane spanning this largest cavity burst, releasing all of the impounded phosphoric acid into the ground.

Quality assurance during installation had consisted of only two one-day visits by an engineer who specialized in roofing membranes. Therefore, it is not surprising that defective seams were not detected prior to filling.

During the forensic analysis, visual observation showed that approximately 0·1% of the seam length (including factory seams and field seams) was defective. It is probable that a higher percentage would have been obtained if a vacuum box had been used instead of visual inspection. It is also probable that a higher percentage would have been obtained if only field seams had been considered to calculate the above percentage.

2.3.7 *Frequency of geomembrane defects*

Consistency of the observations. Sections 2.3.5 and 2.3.6 present data related to frequency of seam defects. Some of these data are expressed as an average seam length exhibiting one defect (e.g. one defect per 7 m (23 ft) of seam), while other data are expressed as a percentage of defective seam length (e.g. 0·5% of the total seam length was defective).

If an average length of seam defect (prior to quality assurance) of 10 mm (0·4 in) is considered, a percentage of defective seam length of 0·1% is equivalent to one defect every 10 m (30 ft). Therefore, the observations made in the above case studies appear to be consistent.

Conclusion regarding frequency of seam defects. It is not possible to draw general conclusions from only six cases. However, since the observations made in these six cases were consistent, the following tentative conclusions may be drawn for analysis and design purposes:

- An average of one defect per 10 m (30 ft) of field seam can be expected without quality assurance by an independent firm, and without adequate quality control by the geomembrane installer.
- An average of one defect per 300 m (1000 ft) of field seam can be expected with reasonably good installation, adequate quality assurance (which implies adequate quality control), and repair of noted defects. (Quality assurance followed by adequate repair drastically decreases the number of seam defects but does not totally eliminate them.)

The average of one seam defect per 10 m (30 ft) *without or before quality assurance* will probably decrease in the future as a result of the increasing use of new, automated methods of seaming which are now available. However, the number of seam defects *after quality assurance* may not decrease significantly because, in the present state of practice for construction quality assurance, great emphasis is put on finding seam defects and repairing them. Nonetheless, the better seaming methods that are now available are highly beneficial for at least the following reasons: (i) less seam repair is required during installation; (ii) frequency of destructive seam testing may be decreased; (iii) although quality assurance of seaming will always be essential, emphasis in the quality assurance efforts may shift toward other areas where improvement is sorely needed such as connections of geomembranes with appurtenances and placement of drainage materials (which is essential for the functioning of leakage collection layers); and (iv) stronger seams are less likely to fail when subjected to stresses.

As a result of the above discussion, a frequency of one defect per 300 m (1000 ft) of seam will be used as a working assumption for analysis and design purposes. If geomembrane panels 6–10 m (20–30 ft) wide are used, one defect per 300 m (1000 ft) of seam is equivalent to 3–5 seam defects per hectare (1–2 seam defects per acre) of installed geomembrane.

As soon as possible, these assumed defect frequencies must be modified as required by conclusions established on a broader base of welldocumented case histories. In the meantime (and in the absence of better data), a defect frequency of one per 4000 m^2 (acre) will be used in calculations for estimating leakage rates in order to size leakage collection layers. This frequency is assumed to include all types of defects, not only seam defects.

2.3.8 Estimation of size of defects

The seam defect documentation reported above addressed primarily the frequency of seam defects. Extensive documentation of defect size does not exist. On the basis of interviews with quality assurance personnel it appears that the maximum size of defects which may still exist after intensive quality assurance is equivalent to hole diameters of the order of 1–3 mm (0·04–0·12 in) for seam defects and possibly up to 5 mm (0·2 in) for special areas such as connections of geomembranes with appurtenances. (This is consistent with the case history presented in Section 2.3.4.) Finally, larger hole diameters, e.g. 10 mm (0·4 in), can be considered to represent larger defects, such as those due to accidental punctures.

There are also defects that cannot be observed by the quality assurance personnel, such as: (i) puncture of the geomembrane during installation of the protective earth cover or granular drainage layer overlying the geomembrane; and (ii) puncture of the geomembrane as a result of stresses due to the weight of the impounded material or traffic related to the operation of the facility. Defects due to these causes may result in hole sizes larger than those referred to above.

For analysis and design purposes, it is appropriate to consider a range of hole diameters from at least 2 mm (0·08 in), to represent seam defects, to at least 10 mm (0·4 in), to represent accidental punctures.

2.3.9 Hole sizes and frequency recommended for design

Guidance regarding hole size and frequency is useful for engineers designing lining systems. As a result of the discussion presented in Section 2.3.7, a frequency of one hole per 4000 m^2 (acre) should be considered, and, on the basis of the discussion presented in Section 2.3.8, two hole sizes are recommended:

- A hole size of 1 cm^2 (0·16 in^2) is recommended for calculations conducted to size the components of the lining system, and, in particular, the leakage detection, collection, and removal system (i.e. to determine the required hydraulic transmissivity or thickness of the leakage collection layer, to select pipe spacings and diameters, to select the sump size, etc.).
- A hole size of 3·1 mm^2 (0·005 in^2) is recommended for calculations conducted to evaluate the performance of the lining system (i.e.

serviceability calculations, such as flow in the leakage collection layer under typical operating conditions).

In other words, the small hole, which probably exists, is recommended for calculations related to typical operating conditions, and the large hole, which may exist, is recommended for calculations related to maximum flow conditions.

It should be kept in mind that the above hole sizes and frequency have been selected with the assumption that intensive quality assurance monitoring will be performed. A frequency of 25 holes/ha (10 holes/acre) or more is possible when quality assurance is limited to an engineer spot-checking the work done by the geomembrane installer. Also, the above hole sizes and frequency do not take into account cases where design flaws or poor construction practices lead to a greater number of seam defects or a large tear in the geomembrane.

2.4 Conclusions on leakage through geomembrane liners

2.4.1 Summary

In Section 2, the results of permeameter tests and water vapor transmission tests were used to evaluate permeation rates through geomembranes. Equations to evaluate leakage rates through pinholes and holes were also presented. Finally, the following recommendations regarding frequency and size of holes to be assumed for analysis and design were made on the basis of field experience:

- a frequency of one hole per 4000 m^2 (acre); and
- two hole sizes, 1 cm^2 (0·16 in^2) for calculations to size the components of the lining system, and 3·1 mm^2 (0·005 in^2) for performance calculations.

2.4.2 Leakage rates

By combining Tables 5 and 6, it is possible to establish Table 7. This table gives orders of magnitude of unitized leakage rates that may be expected when a geomembrane is used alone as a liner.

It appears that the unitized leakage rates due to only one hole per 4000 m^2 (acre) are large, especially for the large hole, while unitized leakage rates due to permeation and pinholes are small. It must be remembered that the unitized rates given in Table 7 are related to a liner comprised of a geomembrane placed directly on the leakage collection layer or other very permeable layer. As indicated in Section 2.3.3, the equation used to evaluate leakage rates through geomembrane holes is valid if the hydraulic conductivity of the leakage collection layer is larger than 10^{-3} m/s (0·1 cm/s), which will often be the case.

TABLE 7
Calculated Unitized Leakage Rates Through a Geomembrane Liner

	Water depth on top of the geomembrane, h_w				
	0·003 m (0·01 ft)	*0·03 m (0·1 ft)*	*0·3 m (1 ft)*	*3 m (10 ft)*	*30 m (100 ft)*
Permeation	0·000 1 (0·000 01)	0·01 (0·001)	1 (0·1)	100 (10)	300 (30)
Pinhole	0·01 (0·001)	0·1 (0·01)	1 (0·1)	10 (1)	100 (10)
Small hole	100 (10)	300 (30)	1 000 (100)	3 000 (300)	10 000 (1 000)
Large hole	3 000 (300)	10 000 (1 000)	30 000 (3 000)	100 000 (10 000)	300 000 (30 000)
	Values of unitized leakage rate in lphd (gpad)				

Notes: The geomembrane is assumed to be underlain and overlain by a very pervious medium such as coarse gravel or geonet. The leakage rate calculated for holes would be significantly reduced if the pervious medium in contact with the geomembrane on one or both sides is sand or a less permeable material. The geomembrane is assumed to be made from HDPE with a thickness of 1 mm (40 mils). The unitized leakage rates (i.e. leakage rates per unit area of liner) were obtained assuming one pinhole or one hole per 4000 m^2 (acre). This table has been established by combining Tables 5 and 6 and rounding up. The considered pinhole has a diameter of 0·1 mm (0·004 in); the small hole has a surface area of 3·1 mm^2 (0·005 in^2), i.e. a diameter of 2·0 mm (0·08 in); and the large hole has a surface area of 1 cm^2 (0·16 in^2), i.e. a diameter of 11·3 mm (0·445 in). The water depths used here correspond to the typical values defined in Section 1.3.6.

It must also be remembered that the unitized leakage rates in Table 7 assume that the soil layer or other material (such as a synthetic drainage layer) directly overlying the geomembrane does not impede flow. This latter assumption is important and its ramifications have not been investigated by the authors. It is likely that, in some cases, a protective soil layer or granular drainage material placed over a geomembrane impedes flow through geomembrane defects. The influence of the overlying material on the flow rate through a defect in a geomembrane liner requires further investigation.

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Part II of this paper, covering Leakage through Composite Liners and Conclusions will follow in *Geotextiles and Geomembranes* 8(2).